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An analytical approach to separate climate and human contributions to basin streamflow variability

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ABSTRACT

Climate variability and anthropogenic regulations are two interwoven factors in the ecohydrologic system across large basins. Understanding the roles that these two factors play under various hydrologic conditions is of great significance for basin hydrology and sustainable water utilization. In this study, we present an analytical approach based on coupling water balance method and Budyko hypothesis to derive effectiveness coefficients (ECs) of climate change, as a way to disentangle contributions of it and human activities to the variability of river discharges under different hydro-transitional situations. The climate dominated streamflow change (ΔQ_c) by EC approach was compared with those deduced by the elasticity method and sensitivity index. The results suggest that the EC approach is valid and applicable for hydrologic study at large basin scale. Analyses of various scenarios revealed that contributions of climate change and human activities to river discharge variation differed among the regions of the study area. Over the past several decades, climate change dominated hydro-transitions from dry to wet, while human activities played key roles in the reduction of streamflow during wet to dry periods. Remarkable decline of discharge in upstream was mainly due to human interventions, although climate contributed more to runoff increasing during dry periods in the semi-arid downstream. Induced effectiveness on streamflow changes indicated a contribution ratio of 49% for climate and 51% for human activities at the basin scale from 1956 to 2015. The mathematic derivation based simple approach, together with the case example of temporal segmentation and spatial zoning, could help people understand variation of river discharge with more details at a large basin scale under the background of climate change and human regulations.

1. Introduction

Environmental change challenges human adaptations (Conway and Schipper, 2011; Foley et al., 2011; Reynolds et al., 2007). Human adaptations start from the awareness of environmental impacts on ecosystem services with positive or negative consequences (Angélil et al., 2017; Pérez et al., 2016; Xu et al., 2016) at different spatio-temporal scales. As the basic provisional service to the ecological-economic-social system, water, with its adaptive utilizations, has been a hotspot in many sectors including research, management, and policy-making (Field et al., 2014; Henriques et al., 2015; Pahl-Wostl and Knieper, 2014). Given water scarcity and increased demand in most part of the world (Mo et al., 2016; Pedro-Monzonis et al., 2015), it is necessary to understand the major drivers of changes in water resources (Fatichi et al., 2015; Shrestha et al., 2017) for sustainability assessment of the coupled human-nature system (Liu et al., 2015), from perspectives of both rational utilization by human (Dang et al., 2016; Li et al., 2014; Oron et al., 2014) and efficient services by water (Batchelor et al., 2014; Fuller et al., 2017).

River discharge is the lumped remaining after the water-energy interactions between land surface and atmosphere, playing a key role in basin hydrology (Luo et al., 2017). It is of great significance not just as an indicator of different water-energy forms and cycles (Marsh and Neumann, 2001), but also an important source for human society and economy (Masaki et al., 2014; Nakayama and Shankman, 2013). The past several decades have evidenced climate

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change (Field et al., 2014) and rapid growth in water project development in many places of the world (Garrote et al., 2016; Henriques et al., 2015; Pires et al., 2017). As a consequence, river discharge of many basins departed significantly from their natural variability. Without a holistic understanding of basin hydrology, particularly the river discharge variability and its causes, the risk in water security is likely to be high.

Basin hydrology consists of processes in the atmosphere down to the land surface and the underground system (Singh et al., 2010). Key factors influencing hydrologic variation can be aggregated into two parts as climate-related (e.g. precipitation, temperature, solar radiation, and so on) and underlying condition-related (e.g. soils, vegetation, human regulations on land surface, and so on). For interactions between land surface and atmosphere systems (Fabre et al., 2016), basin hydrology represents high complexity in process and pattern, especially under a changing climate and enhanced human interventions (Foley et al., 2011; Jaramillo and Destouni, 2015). Given difficulties to quantify anthropogenic effects (regulations of underlying conditions, i.e., Scanlon et al. (2007)) on climate (i.e., air temperature, precipitation, wind, and so on), or changing climate impacts (feedbacks) on land surface processes (rainstorm, flood, drought, and so on.) (Yilmaz et al., 2014; Yin et al., 2017), uncertainties emerge when studying all processes in one study (Dams et al., 2015). Researchers tend to simplify some details of the feedbacks in separating contributions of climate change and human activities (Wu et al., 2017), which made it feasible to focus on basin level discharges.

From a practical perspective, the observed hydrologic events such as river discharges are often a result of complex interactions between climate change and anthropogenic activities (Silveira et al., 2017). This complexity represents a challenge to separate contributions from climate change to observed streamflow variation (Ye et al., 2013). Studies on this complexity could help better understand how and why streamflow varies and informed management decision to adapt future water stresses (Khalil et al., 2005), especially in water scarce regions. For a natural system, climate plays an important role in transitions between wet, normal and dry conditions (corresponding to high, normal and low flows) in river discharge (Goler et al., 2016; Shabalova et al., 2003). Human activities exert additional fluctuations to strengthen or weaken the natural variations (Guo et al., 2015). At a basin level, intensity of human impacts is tightly linked to changes of underlying condition and actual evapotranspiration (AET), which is primarily controlled by regional water-energy patterns (Moyano et al., 2015; Senay et al., 2011). As strengthened human regulations changed land surface more and more, basin hydrology appears with higher complexity. Physically quantifying major hydrologic variables like AET or river discharge with their variations faces challenges. Coupling classic methods of climatology and water balance is of reliable feasibility to comprehensively disentangle contributions to river discharge variations due to climate change and human activities (Qiu et al., 2016; Wang et al., 2016).

Methodologically, therefore, separation of human influences from climate impacts on river streamflow can be categorized into two types. One is based on water balance, where separation of the two can be made through determination of AET. The other is based on water-energy shifts, which reflect some general insights of streamflow variations (Bosshard et al., 2013). It is obvious that the first approach aims at quantitative separation while the latter features particular emphasis on qualitative division under framework of water-energy patterns (Dey and Mishra, 2017).

In theory, separations could be done through diagrammatizing or numerical calculation. The former divides curve decompositions (i.e., Budyko curves (1974)) and framework illustrations (i.e., Tomer and Schilling framework (2009)). The latter includes methods of elasticity (Schaake, 1990), sensitivity (Milly and Dunne, 2002), catchments experiment (Bosch and Hewlett, 1982) or modeling (i.e., implementation of model SWAT (Yang et al., 2016)). In any of the above methods, estimation of AET is essential. Many of them were derivations from classic hypothesis and have modified the climate-based principles (i.e., the Budyko equation consists of two climatic variables, precipitation and potential evapotranspiration) into parameter-regulated real outputs of AET (underlying conditions are considered; i.e., Zhang et al., 2001; Wang and Hejazi, 2011). The introduced parameters often varied with climate, vegetation, and soils, and thus are difficult to quantify.

The variability and difficulty of determining these parameters often introduce some uncertainties for separation of human and climate impacts on river streamflow (Jiang et al., 2015; Ye et al., 2013; Zeng et al., 2015). In this study, we presented an analytical approach based on partial derivatives under the framework of coupling basin water balance and the Budyko hypothesis, which made determination of climatic influences on river discharge variation more simply and mathematically understanding. Furthermore, various scenarios settings for different hydro-transitions in diverse regions for contribution decomposition were conducted. Ideas of temporal segmentation and spatial zoning could help contribution separation working with more details, which would help people understand variation of river discharge and then manage the basin resources better under dual impacts of climate change and human activities. Findings could be a case example for comprehensive studies on basin hydrology in the perspective of complicated ecohydrologic variations in time and space.

2. Study area and data

The Tao River basin (TRB) is the second largest tributary of the upper Yellow River in northwestern China, geographically located between 101°36′E and 104°20′E, 34°06′N and 36°01′, with a total area of 25,527 km^2 and a multi-yearly average annual total of 46.13×10^8 m^3 in discharge (1956–2015). The basin features an elevation range from 1730–4560 m, covers portions of the eastern Tibetan Plateau (4560–2800 m) and southwestern Loess Plateau (2800–1730 m), from upstream to downstream. Annual mean air temperature increased from lower than 2 °C to over 8 °C from the west part of the basin to the east, while precipitation decreased from over 600 mm in the west to about 350 mm in the northeast. High complexity of ecohydrology was found across the whole basin. (Fig. 1) According to the remarkable heterogeneity of hydrometeorology and land cover in space, we divide the whole basin into upper, middle and lower areas along with considering the industrial mode across the TRB. It features a relatively flat topography with open valleys and dominates grasslands in the upper reaches while the meandering river is surrounded by high mountains covered mainly by forests and grasses in the middle reaches. The river flows into Loess Plateau in the lower reaches, where vegetation with low coverage occupied about 21%, resulted in relatively severe water and soil loss. The industrial modes transit from grazing-dominated in the upper area to the rain-fed agriculture-dominated in the lower area, while in the middle area, it features a mixture of forestry, grazing and farming.

We collected hydrometeorological series in or near the TRB from China meteorological data sharing network (http://data.cma.cn) and Gansu Province Bureau of Hydrology and Water Resources Monitoring, including 10 standard weather stations, 22 rainfall gauge stations and 6 hydrological observational stations (5 on main stream and 1 on one of the first-level tributaries in lower reaches, Table 1). We adopted method of double mass curve to check the consistency for each hydrometeorological factor (Searcy and Hardison, 1960). Analogy method (linear) was adopted to interpolate or extend the missing series to build the same length

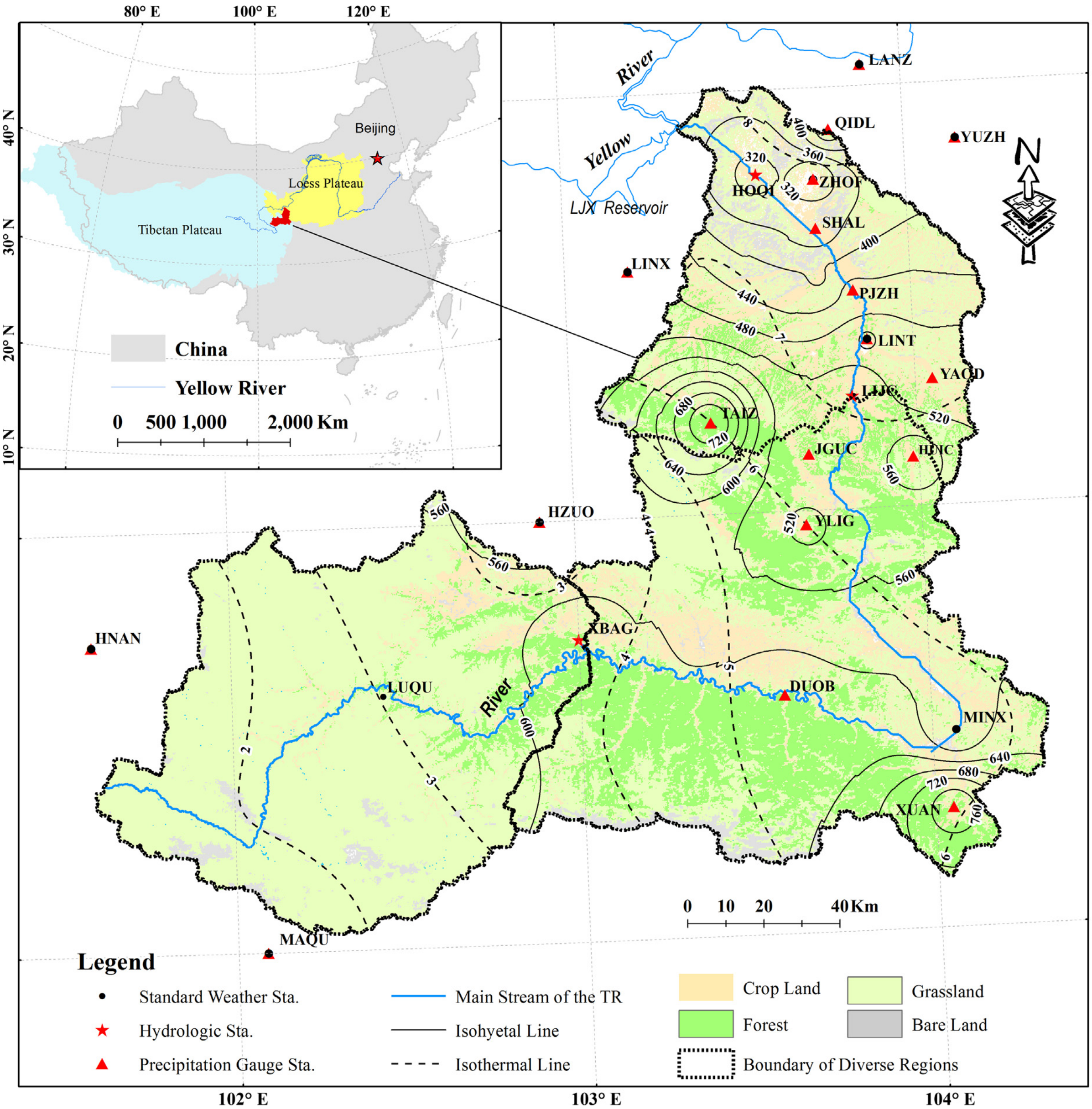

Fig. 1. Location map of the study area, together with isolines of multi-yearly averaged annual air temperature and precipitation across the basin. Distribution of hydrometeorological gauge stations for data acquisition also presented. Land cover map of the basin was used to present the regional geographic, ecological, and hydrological differentiations across the TRB.

Table 1
The overview of the hydrometeorologic datasets used in this study.

Stations	Lon. (°E)	Lat. (°N)	Ele. (m)	Start year	Station	Lon. (°E)	Lat. (°N)	Ele. (m)	Start year
HNAN[a]	101.60	34.73	3350	1951	LINX[a]	103.18	35.58	1917	1951
MAQU[a]	102.08	34.00	3471	1951	LIJC[b]	103.82	35.27	1916	1947
LUQU[b]	102.43	34.60	3202	1967	YAOD[c]	104.05	35.30	2371	1963
HZUO[a]	102.90	35.00	2911	1951	LINT[a]	103.87	35.40	1894	1966
XBAG[b]	103.00	34.72	2796	1960	PJZH[c]	103.83	35.52	1838	1956
DUOB[c]	103.58	34.57	2608	1958	SHAL[c]	103.73	35.67	1819	1935
XUAN[c]	104.05	34.28	2539	1959	ZHOF[c]	103.73	35.78	2011	1965
MINX[a,b]	104.07	34.47	2315	1948	HOQI[b]	103.57	35.80	1768	1954
YLIG[c]	103.67	34.97	2213	1953	YUZH[a]	104.15	35.87	1874	1951
JGUC[c]	103.68	35.13	2183	1953	QIDL[c]	103.78	35.90	2389	1967
HUIC[c]	103.98	35.12	2249	1956	LANZ[a]	103.88	36.05	1517	1951

Sourced from a: Meteorological system; b: Hydrological system; c: Water conservation system

of time series from 1956 to 2015, based on comparisons between the nearest stations. Surface distribution of climatic factors gained by using ArcGIS Geostatistical Analyst tool for interpolation, zonal statistics then implemented to illustrate regional heterogeneity of the factors. Total annual streamflow ($10^8 m^3$) at observational sections were divided by catchment area (Km^2) for regional hydrometeorology analysis in the unit of mm.

Over the past 60 years, there experienced warming and decreased precipitation and river discharge across the TRB (Li et al., 2015). Basin hydrology and water availability face new perspectives. Challenges are critical for water resource planning and management of the TRB as is a source region for water transfer to the water scarce loess area in northwest China. Impacts of climate change and human activities upon streamflow variation are of great importance on water availability with its rational utilization in the area.

3. Methodologies

Conceptual framework, together with technique route of coupling methods of water balance and Budyko hypothesis to obtain the partial differential equation for the derivative determination of the ECs were holistically illustrated in Fig. 2. Estimation of ET_0 was conducted by using the Penman-Monteith equation(Allen et al., 1989). Parameters for the estimation were defined according to local weather observations and field experiments (Pirkner et al., 2014; Li et al., 2015), combined with those suggested in the FAO Irrigation and Drainage Paper (Allen et al., 1989). Observational series of precipitation and river discharge were used to calculate the ECs as input variables in the differential formulas. The elasticity method and sensitivity method were adopted to compute influences of climatic factors on streamflow variation, which provided a comparative assessment of the EC approach outputs. The validated EC approach was used to disentangle contributions of climate change and human regulations on river discharge variations. Separations were conducted under 8 scenarios reflecting different hydrological transitions (Fig. 2.).

3.1. The Budyko equation and its derivations

According to the famous Budyko's hypothesis (Budyko, 1974), the evaporative ratio (AET/P) is as the function of the parameter φ (ET_0/P) (where φ is the FAO aridity index):

$$\mathrm{AET} = \mathrm{P} \times \sqrt{\frac{\mathrm{ET_0}}{\mathrm{P}} tanh\left(\frac{\mathrm{P}}{\mathrm{ET_0}}\right) \times \left[1 - exp\left(-\frac{\mathrm{ET_0}}{\mathrm{P}}\right)\right]} \tag{1}$$

Researchers have developed many types of mathematic expressions or methods (Choudhury, 1999; Donohue et al., 2012; Fu, 1981; Fu et al., 2007; Milly and Dunne, 2002; Porporato et al., 2004; Wang and Tang, 2014; Wang and Zhou, 2016; Yang et al., 2008; Zhang et al., 2001) since the hypothesis proposed. Budyko hypothesis on AET's estimation was based on climatic factors, which provides a considerable basis for separating contributions of climate change and human activities on basin hydrology variability (Donohue et al., 2011; Jiang et al., 2015; Wang and Tang, 2014). In this study, we select equations developed by Fu (1981) (Equation S1) and Zhang et al.(2001) (Equation S2) for a pilot exploration of climate-driven hydrologic variations in the study area. More details about these two equations can be found in the Supplementary Materials.

3.2. Effectiveness coefficient approach based on analytical derivation

Basin water balance could be expressed as:

$$\mathrm{P} = \mathrm{Q} + \mathrm{AET} + \Delta\mathrm{S} \tag{2}$$

where Q is the annual channel streamflow and transferred into runoff depth (mm); ΔS is the basin water storage, which evaporates or transpires in the post time and tends to be zero when given a relatively long time period (Dingman, 2002). Thus, calculation for river discharge could be simplified as the difference between P and AET. To date, regional effectiveness of human's regulation on climatic P is still facing challenge, we consider P as a complete climate-controlled issue. Regional AET in larger watersheds was influenced by climate change coincided with land cover dynamics (Wang and

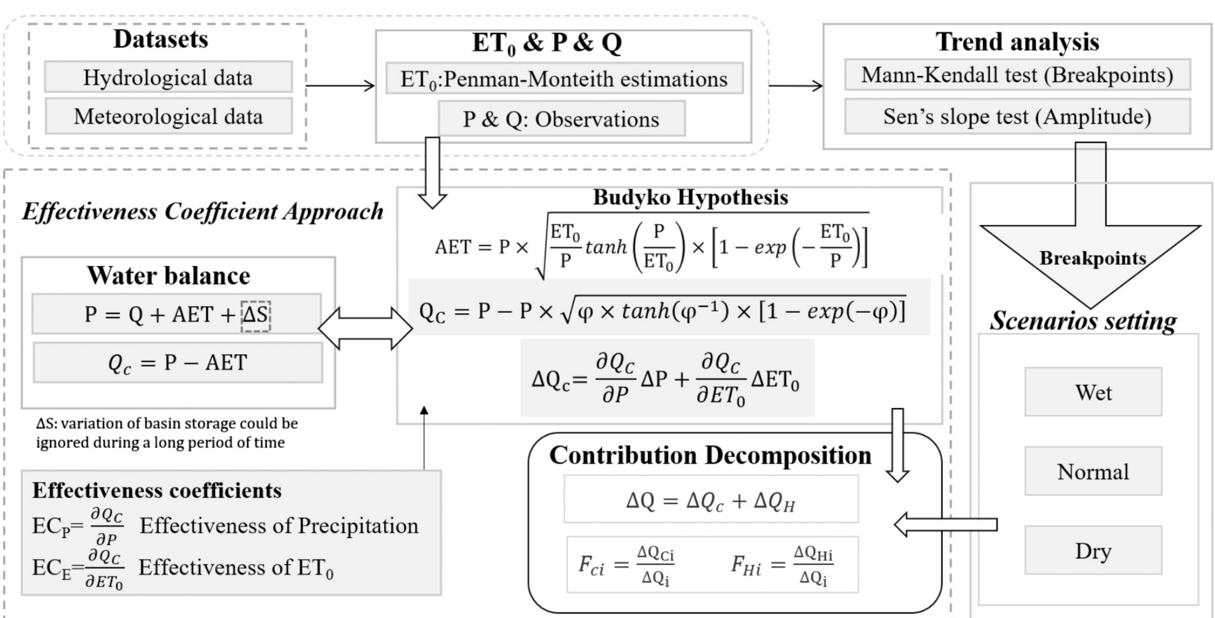

Fig. 2. Framework of coupling methods of water balance and Budyko hypothesis to structure partial differential equation for derivative determination of Effectiveness Coefficients representing influences of precipitation and ET_0 on river discharge variations. Scenarios settings based on hydro-statistics also presented.

Hejazi, 2011). The latter is reformed by anthropogenic impact at different levels. Discharge is determined as transformed from Eq. (2):

$$Q = P - (AET_c + AET_H) \tag{3}$$

where AET_c is the regional AET dominated by climate change, numerically equal to that of Budyko equation (Eq. (1)) derived. AET_H is the AET induced by human activities, both in units of mm. Purely climatically dominated river streamflow (Q_c) could then be described as:

$$Q_c = P - AET \tag{4}$$

where AET is under the framework of Budyko hypothesis, equals to AET_c in Eq. (3).

Set parameter ET_0/P as φ, Eq. (1) could be rewritten as:

$$AET = P \times \sqrt{\varphi \times tanh(\varphi^{-1}) \times [1 - exp(-\varphi)]} \tag{5}$$

The transformation of Eq. (4) is:

$$Q_C = P - P \times \sqrt{\varphi \times tanh(\varphi^{-1}) \times [1 - exp(-\varphi)]} \tag{6}$$

Note $tanh(\varphi^{-1})$ as s, $[1 - exp(-\varphi)]$ as t, Eq. (6) is transformed into:

$$Q_C = P - P \times \sqrt{\varphi \times s \times t} \tag{7}$$

Given independent variables of P and ET_0, changes of river discharge due to climate change could be described as (Donohue et al., 2011; Jiang et al., 2015):

$$\Delta Q_c = \frac{\partial Q_C}{\partial P}\Delta P + \frac{\partial Q_C}{\partial ET_0}\Delta ET_0 \tag{8}$$

Parameters $\frac{\partial Q_C}{\partial P}$ and $\frac{\partial Q_C}{\partial ET_0}$ are defined as effectiveness coefficients (EC_P and EC_E) of P and ET_0 to the changed discharge. Calculation of the partial derivatives could be a further deduction of ΔQ_c. Results of partial derivatives of Q_c to P and ET_0 are respectively as the followed:

$$EC_P = 1 - \sqrt{\varphi st} - \frac{P}{2\sqrt{\varphi st}} \times \left[\left(-\frac{\varphi st}{P}\right) + \varphi t\left(\frac{1}{cosh^2(1/\varphi)} \times \frac{1}{ET_0}\right) + \varphi\left(\frac{\varphi st - \varphi s}{P}\right)\right] \tag{9}$$

$$EC_E = \frac{-P}{2\sqrt{\varphi st}} \times \left[\frac{st}{P} + \varphi t\left(\frac{1}{cosh^2(1/\varphi)} \times \left(-\frac{1}{\varphi ET_0}\right)\right) + \left(\frac{\varphi s - \varphi st}{P}\right)\right] \tag{10}$$

Given the observed series of P and P-M method based estimation of ET_0, the climate dominated change of river discharge (ΔQ_c) could be determined directly under the framework of Budyko hypothesis.

3.3. Elasticity method and sensitivity method

The elasticity method and sensitivity method were chosen to comprise with the effectiveness coefficient approach. Climate elasticity method proposed by Schaake (1990) has been considered to quantify changes of streamflow under climate change including variations of long term precipitation and potential evapotranspiration.

$$\Delta Q_c = \left(\varepsilon_P \frac{\Delta P}{P} + \varepsilon_{ET_0}\frac{\Delta ET_0}{ET_0}\right)Q \tag{11}$$

where ε_P and ε_{ET_0} are elasticity, representing the effects of P and ET_0 to streamflow variation, respectively.

In the sensitivity method, changes of long-term streamflow could be expressed when considering under climate change:

$$\Delta Q_c = \beta\Delta P + \gamma\Delta ET_0 \tag{12}$$

where $\beta$and γ is the sensitivity index of streamflow to variations of precipitation and potential evapotranspiration.

More details and the calculation method of the above index ($\varepsilon_P, \varepsilon_{ET_0}, \beta$ and γ) can be found in the Supplementary Materials (Equations S4–S6, S8–S9).

3.4. Decomposition of contributions

The total change of streamflow can be described as:

$$\Delta Q = \Delta Q_c + \Delta Q_H \tag{13}$$

Generally, anthropogenic impact strengthened along with economic and social development in certain regions. Also, in most of area inhabits people, both climate change and human activities influence hydrologic process including all time spans featuring wet, normal or dry at multi-yearly durations. The above three hydrologic characteristics, along with effectiveness (or elasticity and sensitivity) exploration before and after the changepoint would advance the study with more details. For a given time span responding to any kind of hydrologic transition, Eq. (13) would be:

$$\Delta Q_i = \Delta Q_{ci} + \Delta Q_{Hi} \tag{14}$$

where i = 1, 2, 3⋯; represents the time span responding to hydrologic transition among wet, normal or dry conditions containing at least one change breakpoint.

For the contribution percentage of climate change and human activities, expressions are:

$$F_{ci} = \frac{\Delta Q_{Ci}}{\Delta Q_i}, \quad F_{Hi} = \frac{\Delta Q_{Hi}}{\Delta Q_i} \tag{15}$$

where F_{ci} and F_{Hi} are percentage of impact contributions of climate change and human activities on discharge variation, respectively.

Results of decomposition by EC approach would be compared with estimations by methods of Elasticity (Schaake, 1990) and Sensitivity (Milly and Dunne, 2002) described as Eqs. S3–S9 in the Supplementary Materials. Eqs. 8, 11 and 12 make sense of how the three approaches functioning on explanation of climate change influences on streamflow variability. Time ranges could be defined according to objectives for different studies, in a relatively long period of time. Computationally, it is intuitionistic for effectiveness coefficients to explain climate change impacting on streamflow variation. The elasticity indexes are good at clarifying the logistical linkages among relative departures of the variables. The sensitive method focuses on sensitivity of channel process to climatic variations. Ideas of the three methods are from different aspects to explain the impact-respond loop between the climate-river systems. The EC approach is mathematically based on partial differentiation, emphasizing the original intention of climatological hypothesis on AET's estimation under the framework of Budyko method.

3.5. Statistics

Statistics for time series were mainly conducted by using Mann-Kendall test (Kendall, 1955; Mann, 1945) and Sen's Slope method (Sen, 1968) for estimation of variation trend and amplitude for all variables in different zones.

4. Results

4.1. Variation of annual ET_0 and AET

Estimations of ET_0 by the P-M equation were validated through comparing with 20 cm evaporation pan-observed series. The latter were modified by correction coefficients in diverse regions of the TRB (Li et al., 2015). Results revealed a relatively high accuracy with a Nash coefficient of near 0.85. Water balance method was used to validate the Budyko equation-based estimation of AET. Comparison between Budyko equation estimations and P minus runoff in diverse regions of the basin resulted in evaluation values of 0.89 and 0.78 for correlation coefficient and the Nash coefficient, respectively, meant a satisfactory applicability of the approach (Li et al., 2015).

Sen's slope method was used to test the variation amplitude of ET_0 and AET in the three diverse regions of the TRB, along with statistics of other hydrometeorological factors (Table 2). In the past 60 years, there experienced an overall increase of ET_0 across the whole basin. Average annual total of ET_0 were estimated approximately in 619, 620 and 679 mm in the up, middle and down streams, respectively by zonal statistics, maintained rising from the semi-humid cold region to the semi-arid warm region in space. Highest ET_0 increase rate was found in the middle stream, while in the upstream and downstream, ET_0 fluctuated with relatively smaller increase rates. Annual total of AET estimated by Budyko method were averaged approximately in 327, 350 and 316 mm in areas of the grassland dominated upstream, the forest-grassland dominated middle stream and the sparse land cover and arid-cultivation dominated downstream, respectively. Increasing rate of AET was higher in the upstream than that in the middle stream, while there presented a slight decrease trend in the downstream. River discharge (Q) presented decreasing in all the three regions. Dramatic reduction was found in upper reaches at a rate of −2.682 mm/a (Table 2).

4.2. Influential index exploration for the three approaches

4.2.1. Value distribution of effectiveness coefficients

Effects of P and ET_0 to variation of river discharge represented by the two parameters of EC_P and EC_E could be determined according to Eqs. (9) and (10). Pilot study resulted in values of EC_P ranging from 0.11 to 0.87 while that of EC_E, from -0.62 to -0.02 in the study area. Patterns of the calculated parameters compare to P and ET_0 were illustrated as in Fig. 3. Some of the extreme values could not connect into lines because of the data isolations. Plus and minus signs meant enhancive or suppressive effectiveness of P and ET_0 to streamflow changes. Size of the absolute values corresponds to effective intensity, fitting into positive correlation (absolute values), mean that the increment of runoff by increasing precipitation is tending to be balanced by the loss induced from potential evapotranspiration.

4.2.2. Comparisons with the other two approaches

Suitability of effectiveness coefficient (EC) approach evaluated by comparisons between calculations of ECs and the other two index-based methods of elasticity (EI) and sensitivity (SI). EC approach in this study was analytically derived from Budyko hypothesis. Elasticity approach developed by Dooge et al. (1999) and Arora (2002) separately were in different forms but same mechanism on measuring the streamflow elasticity to climate change. We used the determined F(φ) in Fu's equation (1981) to derive and obtain values of the elasticity index. Sensitivity approach by Milly and Dunne (2002) and parameter derivations by Li et al.(2007) based on Zhang's equation (2001) were referenced to estimate the sensitivity index.

The most significant linear relationship between P-induced and ET_0-induced influences was found under the framework of elasticity method, for the inherent constraint of values sum of 1 (Eq. S6 in Supplementary Material; linear slope in Fig. 4 is 1). Slope of sensitive fittings is mild and trends to the position with a little shift

Table 2
Multi-yearly averaged annual amount of the hydrometeorological factors with their Sen's slope tested variation amplitudes in diverse zones of the TRB (1956–2015).

Zones*	Average Annual (°C, mm)					Sen's Slope (°C/a, mm/a)				
	T	P	ET_0	AET	Q	T	P	ET_0	AET	Q
U	1.50	582	619	327	218	0.014^{***}	-1.047^{+}	0.200	0.476^{+}	-2.682^{***}
M	5.95	575	620	350	225	0.023^{***}	−0.566	1.468^{***}	0.199	-1.979^{***}
D	7.10	470	679	316	118	0.019^{***}	−0.802	0.840^{**}	−0.039	−0.219
B	4.85	533	645	331	185	0.019^{***}	−0.894	0.674^{**}	0.216	-1.217^{**}

* U, M, D and B represent area of upstream, middle stream, downstream and the whole basin. ***, **, * and + indicate that values are significant at levels of $P \le 0.001$, $P \le 0.01$, $P \le 0.05$ and $P \le 0.1$, respectively. Others are not significant for Sen's slope test. Meanings for all superscripts maintain same in the rest part of the paper.

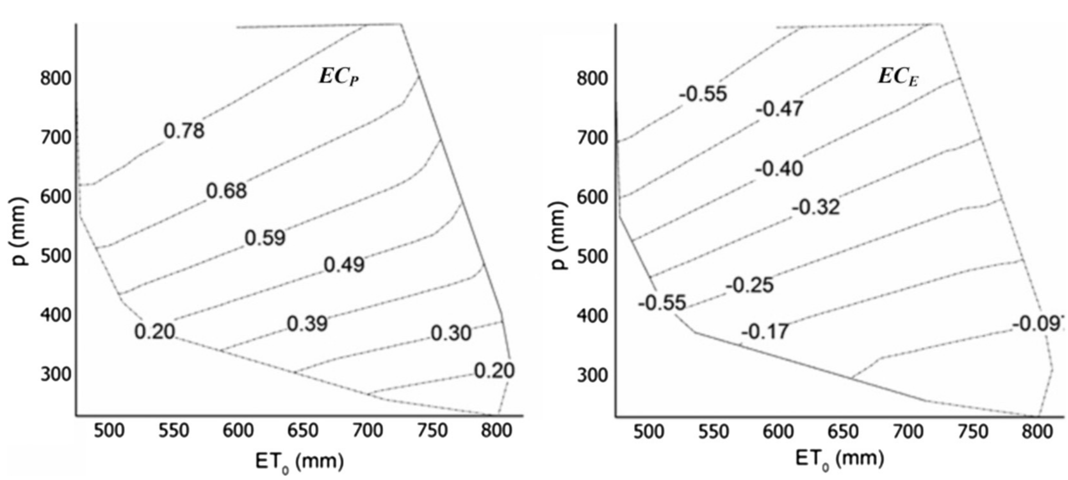

Fig. 3. Value patterns of effectiveness coefficients ECP (Left part) and ECE (Right Part) along with the variation of ET_0 and P across the TRB. Solid line in the boundary meant non-value, while the dotted boundary indicated outsourcings of the extremes.

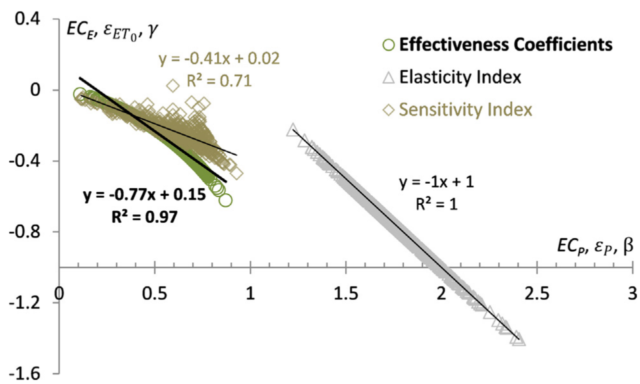

Fig. 4. Comparisons between parameters measuring influences of P and ET_0 on streamflow changes based on different methods. Abscissa values are effective measures of P while the ordinate ones are of ET_0.

Table 3
Average values of the influential index for different approaches in diverse regions of the TRB.

Zones	Approaches*					
	EC		EI		SI	
	EC_P	EC_E	ε_P	ε_{ET_0}	β	γ
U	0.63	−0.33	1.66	−0.66	0.69	−0.26
M	0.62	−0.32	1.77	−0.77	0.67	−0.29
D	0.46	−0.21	1.85	−0.85	0.52	−0.20
B	0.55	−0.27	1.76	−0.76	0.61	−0.24

* Methods or approaches in abbreviations of EC, EI and SI represent those based on effectiveness coefficient, elasticity index and sensitivity index, respectively.

from ECs line. Reason may lie in the parameter ω introduced to reflect vegetation regulations on regional AET (Zhang et al., 2001), which would made the land surface process be more sensitive to ET_0. All the indexes were computed in the three diverse regions across the TRB. Data experiments resulted in larger range of elasticity index, while parameter values were smaller according to the other two methods, numerically below 1 in absolute values (Fig. 4). Index reflecting climatic P showed positive effectiveness on streamflow variation, while that reflecting the climatic ET_0 showed negative. Absolute averages of parameters derived from approaches of EC and SI decreased from upstream to downstream, while that from EI method increased (Table 3), corresponding to the different mechanism between the three approaches, reflecting influences of spatial heterogeneity of water-heat conditions with their interactive effects on climate driven variations on streamflow across the basin. Streamflow variation was more sensitive in the semi-humid and headwater area of upstream.

4.3. Contributions of climate change and human activities on streamflow variations

4.3.1. Discharge variation and specific hydro-transitions

Variations of discharge presented overall decreasing in all the monitoring stations-controlled diverse regions of the TRB, during the time period from 1956 to 2015. Breakpoints of the time series were identified by using different statistic methods of Mann-Kendall, Pettitt, Buishand, the Standard Normal Homogeneity (SNH). Results showed highly agreement of variation trend and time of change among different region of the basin by using the methods. Time of the identified breakpoints were very close to the year of 1991. For example, Mann-Kendall method tested into a $UF_k = UB_k$ combined with $UF_k<0$ at the year of 1991 (the nearest one). The significant decline was found 8–9 years later ($|UF_k| > U_{0.05}$; i.e., in Fig. 5, the year of 1999) in all the three reaches, but with different variation amplitudes (Table 2). Annual total of the 60-year observations were listed and we define the year corresponding to the largest 30% as the wet ones (annual runoff depth $\geq$ 206 mm) and the smallest 30% (annual runoff depth $\leq$ 142 mm) as dry ones, the rest as the normal, which was close to the division result gained from probability statistics (given data settings as $P \leq 37.5\%$, $37.5\% < P \leq 62.5\%$ and $P > 62.5\%$ for hydrological years of wet, normal and dry, respectively) but with more coherence for analysis. Distribution of the hydro-characteristics in years is illustrated as in Fig. 5.

Given the overall variation of the river discharge, there were hydrologic transitions with smaller amplitude before and after the breakpoint of the year 1991. Time series corresponding to specific hydro-characteristics, or that of approximately continuous transformation from combinations of wet/normal/dry to others were selected to design scenarios for contribution separations

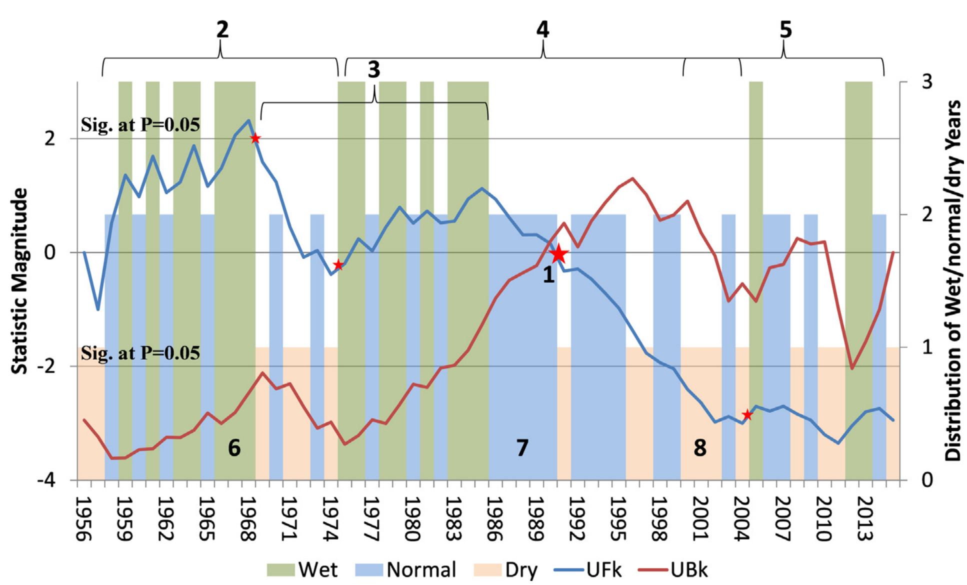

Fig. 5. Mann-Kendall method tested variation of the annual discharge across the TRB, represented by observational series from the lowest station of HOQI (Fig. 2). Distribution of wet/normal/dry periods were also illustrated. Numbers 1, 2 and 3 on the right vertical axis represent dry, normal and wet years in the observed series. Red stars indicate the variation breakpoints. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Table 4
Scenarios for separating contributions of climate change and human activities on streamflow change during multiple periods featuring different hydrologic variations. Values of hydrometeorological factors at the year of breakpoint (BK) were statistically included in the post-change period.

No. of Scenarios	Time Period	Length	Breakpoint	Characteristics*	Note
1	1956–2015	60	1991	Wet-normal to normal-dry	Overall
2	1958–1974	17	1969	Wet-normal to normal-dry	Pre-BK
3	1969–1985	17	1975	Normal-dry to Wet-normal	Pre-BK
4	1975–2004	30	1991	Wet-normal to normal-dry	Across
5	2000–2014	15	2005	Normal-dry to Wet-normal	Post-BK
6	1956–2015	60	1991	Wet	Across
7	1956–2015	60	1991	Normal	Across
8	1956–2015	60	1991	Dry	Across

* There was no absolutely continuous transformation like "from wet to dry" according to data processing. For more concision in statement, we substitute terms like "wet-normal to normal-dry" by "wet to dry", vice versa. Scenarios 6, 7 and 8 were set for diagnostics of main driven factor in the pure wet, normal and dry years during time period from 1956 to 2015.

(Fig. 5 and Table 4). Minimum length of statistical period was set to 5 years. All parameters under different scenarios were calculated for separations of the climate- and human-due effectiveness on the varied river discharges.

4.3.2. Variation of observed discharge under different scenarios

Observed series of streamflow were divided by the area of catchment between hydro-sections (Fig. 1) for statistics in same unit (in mm). Given the determination of ΔQ_{ci} under the Budyko hypothesis, observed ΔQ_i is the base for separation of the influence by human activities on streamflow changes (ΔQ_{Hi}). For the 8 scenarios, there were 2 (Scenarios 3 and 5) set for the transformation from dry to wet, corresponding to increase of river discharges. Most of the other 6 presented reduction of streamflow during the variation, except for scenario 8, the separation under the dry regime between pre- and post-change of 1991 over a 60-year time span, the streamflow in downstream increased. It could be found that the overall decrease of basin discharge was mainly due to flow reduction in the up and middle streams (Fig. 6).

4.3.3. Comparisons between index-based separations by different approaches

Averages of index values in Table 3 were used to separate the climatically influential contributions. Climate-driven changes of streamflow (ΔQ_{Ci}) by the three index-based methods were verified as high concordance (Fig. 7). Correlation coefficients between Approach EC and EI/SI were 0.986/0.998. The overlapping of proofs to each other indicated considerable suitability of the three methods for decomposition of climatic influences on streamflow changes in the study area.

4.3.4. Quantified influences of climate change and human activities on streamflow variations

Results were found close to each other in ratios when the three methods were applied in diverse regions under same scenarios. For example, contribution ratios under scenario 1 were found 49% and 51% by using the EC and EI approaches, while by using the SI approach, ratios were 51% and 49%, quite closely. For writing concision, we use achievements derived by EC approach to present the contributions of climate and human activities under different situations of hydro-transitions (Table 4).

Absolute influences of climatic factors and human regulations could be determined by EC approach under different scenarios in diverse regions. There presented remarkable differences corresponding to various situations. Take results from scenarios 6, 7 and 8 as examples, human activities put obviously negative influences on river discharge under all the three scenarios in upper and middle reaches, although it was found positive influences in lower reaches during wet and dry periods (Fig. 8). Over grazing

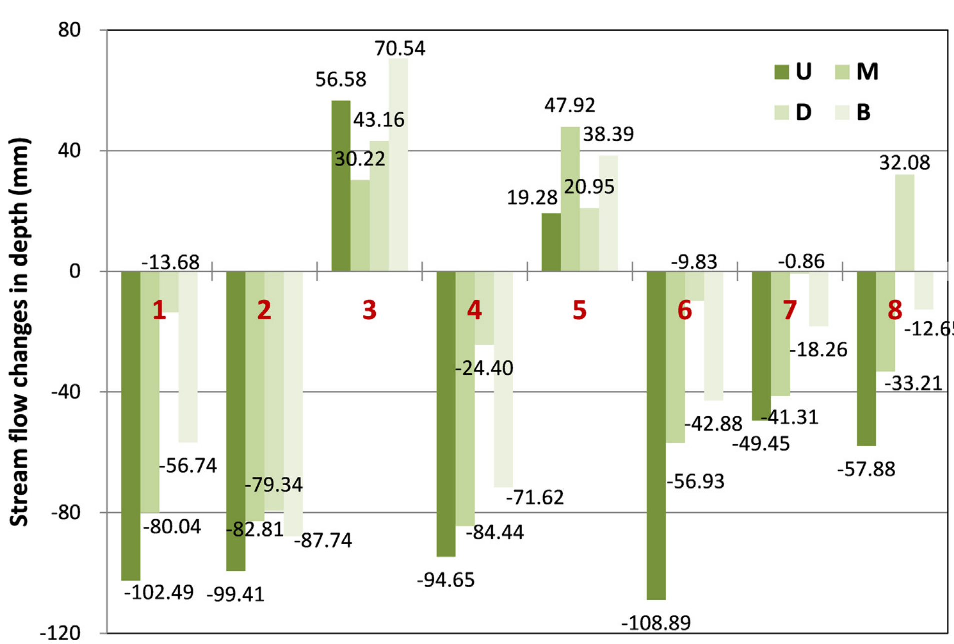

Fig. 6. Changes of observed discharge under different scenarios in the diverse regions of TRB.

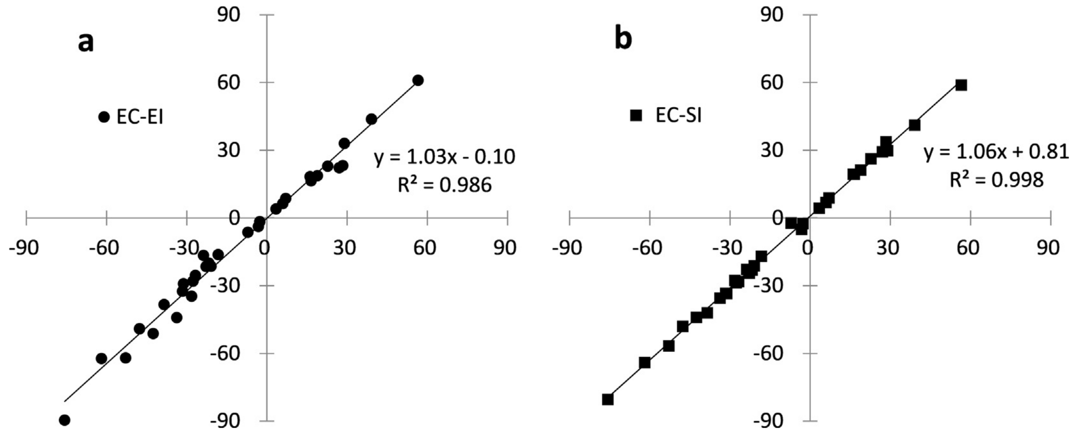

Fig. 7. Comparison between climate-dominated variation of streamflow (ΔQ_{Ci}) derived from different methods (a, Effectiveness Coefficient (EC) vs Elasticity Index (EI); b, Effectiveness Coefficient (EC) vs Sensitivity Index (SI)).

and human regulations in rangelands in upper reaches, along with extension of agriculture and varied cuttings of trees in middle reaches might lead to strong influences of human activities on river discharges there. During the period of dry hydro-years, human issues played an important role in streamflow increase in the downstream when compared before and after the changepoint. Reasons might lie in the precipitation characteristics and human regulations on the hilly arable lands in the area. The semi-arid farming ecosystem would decline when drought occurred. AET in the area would be suppressed. Also, near-bare land could facilitate generation of land surface runoff as rainfall in the area generally presented in a mode of short-term and high-intensity.

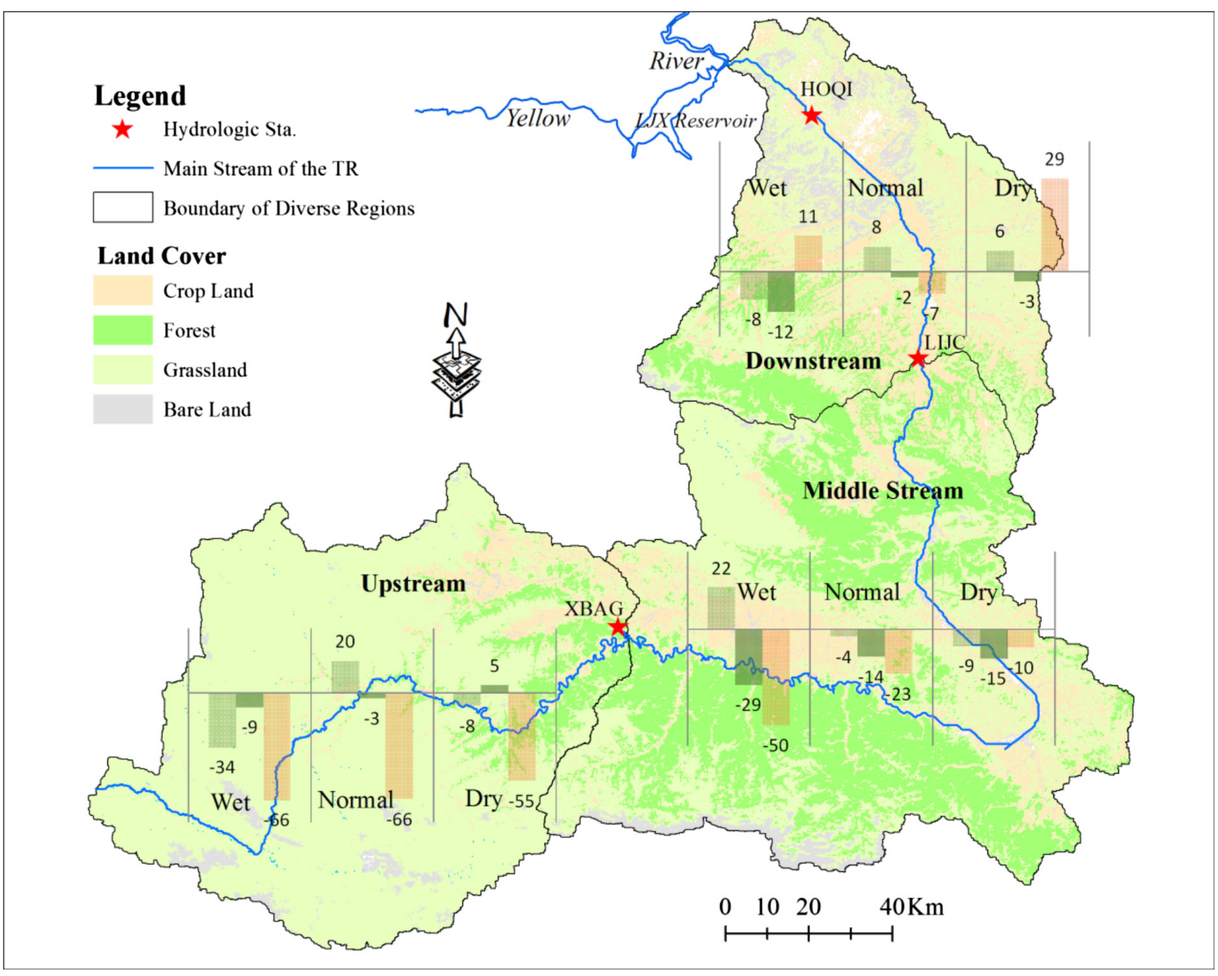

Fig. 8. Climate change due river discharge variation determined by EC approach, together with the disentangle partition from observed variations showing human regulations impacts in diverse regions of the TRB. Scenarios of hydrologically wet (No. 6), normal (No. 7) and dry (No. 8) conditions were considered as examples to illustrate. Bar graphs organized sequentially in colors of light green, green and orange, representing influences of precipitation, ET_0 and human activities in river discharge variations (absolute value of change, mm). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

4.3.5. Contributions of climate and human activities to streamflow changes

There were separately 3, 4, 5 and 4 scenarios which were testified with climate dominated changes in areas of the up, middle, downstream and the whole basin, respectively. Statistics at basin scale presented an overall mean of the other zones (Fig. 9). Contributions of the two factors on streamflow change in diverse regions presented very different in time. Impacts by human activities were less than that of climate change in earlier stages. Influences of human activities were found considerable in the grassland covered semi-humid upstream, while climate change functioned remarkably in the sparse vegetation and rain-fed farmland covered semi-arid loess area in the downstream under most of the scenarios.

Most of the transitions between different hydrometeorological conditions like "wet to dry" (Scenarios 1, 2, 4) or "dry to wet" (Scenarios 3, 5) witnessed climate dominated streamflow changes. Contribution ratios of climate change averaged into 55% and 57.5% for the two variation patterns, respectively. Although remarkable differences were also found in the diverse regions, e.g. scenarios 1 and 4 (wet to dry) in upstream, human activities contributed much more. Reasons might lie in changes of underlying conditions by artificial regulations during the period, i.e., both grazing and fencing conservation facilitate vegetation regeneration (Wu et al., 2009), which consequentially led to more water consumption through AET to satisfy physiological requirement for vegetation growth.

According to separations in wet years, streamflow decrease induced more by human activities in the semi-humid part the basin (upper and middle reaches, (Fig. 9U and M, scenario 6), while in the lower semi-arid reaches, streamflow change controlled mainly by climate change (Fig. 9D, scenario 6). The slight decrease in downstream in normal times (Fig. 6, scenario 7) was mainly human-induced. Climate change made a positive effectiveness, which a compensation to the negative influence by human activities (Fig. 9D, scenario 7).

It was interesting that the increase of streamflow during dry years in the semi-arid region was found mainly induced by human activities (Fig. 9D, scenario 8). The reason might lie in low survival rate of the rain-fed ecology in dry years and the rainfall characteristics in the region (i.e., short term duration, severe intensity). Instantaneous effectiveness to land surface flow due to climate change might be amplified by artificial regulations of underlying conditions.

Primarily, climate change such as increase of T and decrease of P (Table 2) led to the first-step decrease of river discharge in the

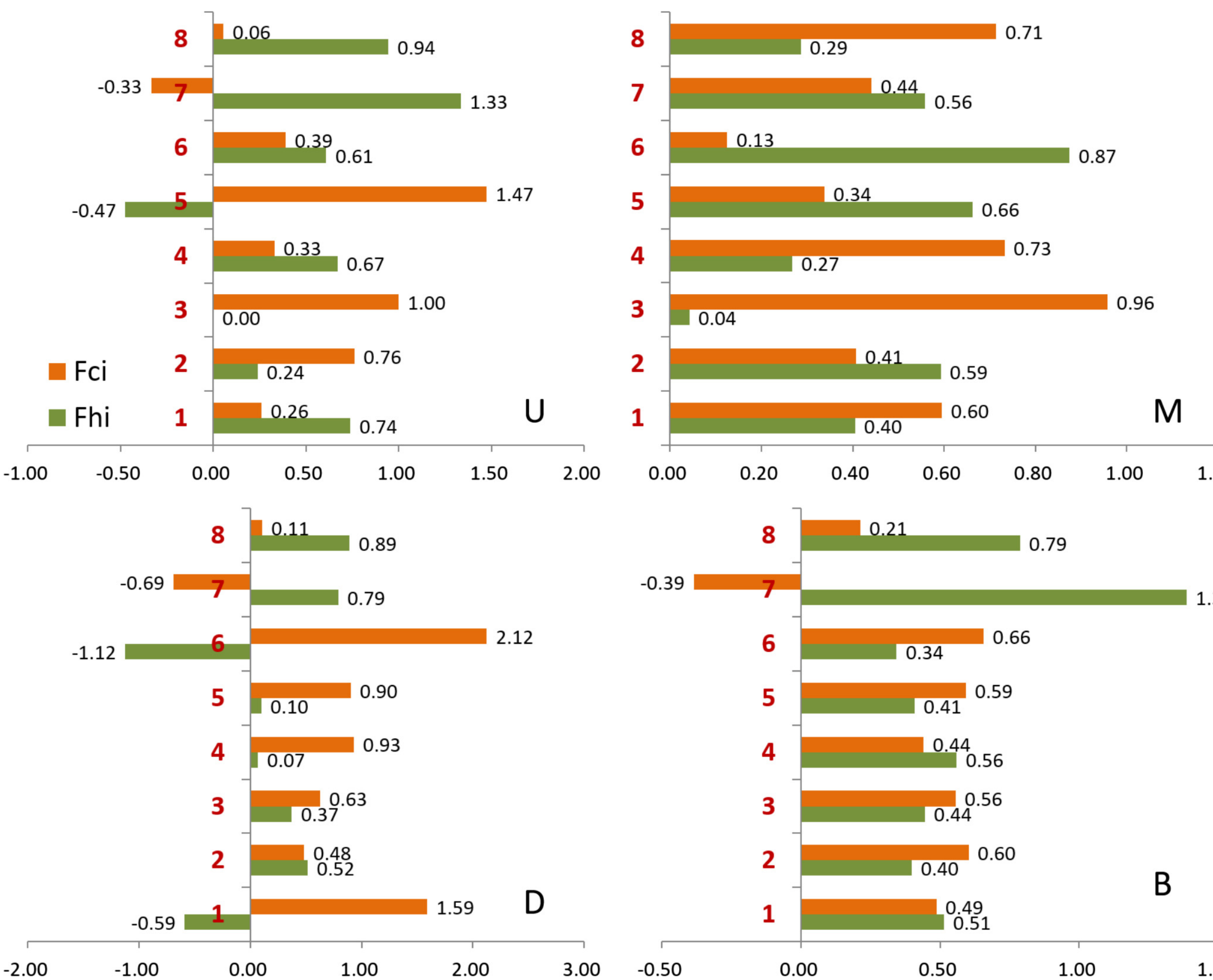

Fig. 9. Relative contribution of climate change and human activities to streamflow changes under different scenarios in diverse regions of the TRB. Vertical coordinates representing the designed scenarios. Opposite values in sigh indicate compensations to the streamflow increase/decrease induced by the dominated factor.

region (Li et al., 2015). Contribution ratios of climate change went into 26%, 60%, 159% in areas of the upper, middle and lower reaches of the TRB during the period from 1956 to 2015, before and after the change breakpoint at the year of 1991. Human activities played a second-step negative role in the decreased streamflow in upper and middle reaches, while that in lower reaches, a positive compensation to climate-induced reduction in river discharges. Overall, contribution ratios of climate change and human regulations on streamflow decrease were 49% and 51% at the basin scale during whole period. The latter functions a little more.

5. Discussions

Given the overlay of anthropogenic regulations on nature, interactions between land surface process and atmospheric system become more and more complicated. Climate does not change by its own, human activities could contribute to alter components in atmosphere, which might lead to more complexity of climatic evolution. Although estimations of ET_0 by P-M Equation were mainly based on modification of local features, the terminology of climate change in this study would still include climate changes induced by human systems. That's to say, separated contribution of climate change on streamflow might have contained portions from human regulations. At this stage, we could not get material to distinguish human activity-induced climate changes. Also, large basin generally features complicated eco-geographical and hydro-geomorphological differentiations. Unequal distribution of the finite monitoring stations are always near people's habitats. Uncertainties the above issues might cause are what we would like to critically tackle in the future.

Streamflow (Q) in long term would ultimately defined by difference between P and AET. Given the observed P and Q, AET by different drives (climate change-related or human regulation-related) are playing key roles in basin water balance. For AET estimation, Budyko hypothesis emphasizes more at climate part, or even the framework set for AET calculation is just including P and ET_0. This is fortunate for studies in which the relatively pure influence from climate change on hydrologic process needs to clarify. Most of the derivations for AET estimation introduced new parameter (i.e., m in Fu's equation or ω in Zhang's equation) to reflect possible influences of underlying conditions. Achievements might have included the part induced by human activities to the vertical process, or at least there hides challenges on parameter settings to reflect that clearly, especially in ecotone-featured basin with high complexity of ecohydrology.

Effectiveness coefficient approach we present in this study is based on Budyko hypothesis and derived simply by mathematically differential deduction. Auxiliary variables against the dependent one (ΔQ_C) are only the climatic P and ET_0, which made the separation easier to understand and conduct. Ideas of EC approach could also support to distinguish human-induced changes in AET, which could be helpful for assessment of land surface ecology by artificial regulations, including cultivation or grazing.

Observed change of streamflow might be less than the absolute amount induced by climate change or human activities. Consequences of impacts are lumped in river discharges. Given the excess of one influential factor induced, the other one functions as compensation. We consider it a realistic one when contribution ratio was over 100% in separations.

Under the climatological hypothesis of the Budyko method, regional AET was estimated by P and ET_0. If land surface ecology is supported (or partially) by underground system, especially where the annual AET is more than P, like most desert ecosystem in the plain area of China's inland river basins, EC approach would lead to huge uncertainties and might not to be applicable.

6. Conclusions

We take the Tao River Basin as the study area to clarify climate change or human activity induced impacts on river discharge variations. Combined with water balance method, the classic equation of Budyko hypothesis were adopted for diagnosis of hydrometeorologic processes in diverse regions of the basin. An analytical derivation approach (EC) based on the hypothesis was developed to conduct separations under different hydro-transition scenarios. Main conclusions are as follows.

1. Climate induced runoff changes separated by EC approach presented good correlations with those distinguished by elasticity method and sensitivity method. The approach was verified be applicable for contribution separations of runoff changes.
2. Statistically, effectiveness of climate change and human regulations on streamflow variation may compensate to each other at large scale or during a long time period. Different hydro-transition designs in diverse regions featuring heterogeneity of geography and ecology could help to understand contribution of the driven factors with more detail.
3. There experienced complicated variations of streamflow across the TRB. Separations brought about different results in diverse regions under various hydro-transitional scenarios. Climate dominated runoff increase during dry-wet transitions, while human activities strengthened the wet-dry transitions in the area. Especially, runoff decreases in semi-humid regions were mainly due to human regulations, although in the semi-arid area, it was human regulations leading a positive influence to the increased river discharge in dry years. Overall, river discharge declined obviously as the whole at the basin scale. The decreased variation was separated into contribution ratios of 49% and 51% for climate change and human activities, respectively, during the time period from 1956 to 2015.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at https://doi.org/10.1016/j.jhydrol.2018.02.019.

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